Student questions: Klaus Lackner colloquium on "Balancing the World's Carbon Budget"
3/23/16

Question 1: How long do you think it would take for a project like this to have a noticable impact on global CO2 levels?

This depends on your choice of a scenario of how fast the world choses to address the climate change problem. For this answer I assume that there is impetus to find a solution to the problem and that research into the development of direct air capture is supported. I would argue that over the next 3 years or so the basic technology will be demonstrated and established at a level that feasibility is not in question. In about 5 years you could be at the start of a large commercial implementation. Assume that the motivation to do that actually exists. For example, it may become a regulatory requirement that all CO2 emissions are balanced by capture. If that were the case you can look at other examples of a wide range of technologies who demonstrate that a transition from small scale to large scale can happen in about two decades. The automobile is a good example. There were practically no cars in 1900. If you look at a picture of New York City in 1925, there are cars everywhere. The first commercial jet plane was put in service in 1951, the transition to jet planes had been completed well within the 1960s. France faced a serious energy issue in 1974, because it relied on oil for producing electricity, and the price of oil increased 20fold. Therefore, France decided in 1974 to transition to nuclear energy. By 1990, this transition was essentially complete. China built a huge coal based electricity infrastructure, bigger than what the entire infrastructure in the US in about 20 years. If the political will exists I would argue you are looking at a similar time constant here as well. However, after such a time of rapid growth the system can remove a significant amount of CO2 but for the CO2 to come down the machines have to run a long time. So if you reach the level of current emissions and you apply it to drawing down CO2 it would take you roughly 50 years to pull the CO2 back by 100 ppm. So by the end of the century the CO2 could be back were it belongs.

Question 2: It was mentioned that rain and humidity raised issues with the capture of CO2. How severely, if at all, would these conditions limit potential areas to construct these devices?

Our apparatus works best in dry climates. So we like deserts, particularly deserts that have access to some water. E.g. like here from the Colorado River, or because we are close to the ocean. We aim to work with salt water, but the salt water design feature is still under development. We do not know yet how much it hurts to be in a rainy climate. While it rains, we presumably stall completely. When it is very humid our performance is reduced. However, what we lose is not so much the capacity to collect CO2 but the partial pressure at which we deliver it. So the question is whether we can design for different climes. I have written a paper with Steve Goldberg, where we had a design for a cold rainy place, the Kerguelen Islands in the Southern Indian Ocean. It turns out we could make it work, but energy cost was significantly higher than in the desert.

Question 1: You mentioned a need to manufacture 10 million units per year. How would you acquire the infrastructure to build that many units?

If you want to keep up with current world emissions, you would need to operate 100 million units. If they last a decade this would mean a production capacity of 10 million units per year. This is a large industrial capacity but not so large that it could not be done. Assume the manufacturer of these units gets paid and therefore has an interest in selling these units, then it is just like selling other things. Between 2008 and 2014 the number of cars built per year increased from 70 million units per year to 80 million units per year. So this particular industry managed to procure the industrial capacity necessary to support this kind of growth. It won't work unless there is an economic incentive to make it work. But with the economic incentive it is perfectly feasible.

Question 2: Even if we removed all the CO2 you expect to from the system, where would we store it? It did not seem like we can re-use it in sufficient quantities, so it would have to be stored somewhere where it would not leak back into the system.

If you stopped using fossil fuels and produced synthetic fuels to store energy for the transportation sector and for the times the intermittent renewable energy is not available, you could actually close the carbon cycle and there would only be need to store CO2 if you already overshot the safe limits of CO2 concentration in the air. If you don't do that, but keep relying on fossil fuels you would need to have storage to store all the CO2 that is produced from fossil fuels. There are three large reservoirs to consider, one is the ocean, the second are underground reservoirs, the third are solid carbonates that are produced from silicates and would be stored on the surface of the planet. I teach a class on this topic as part of a carbon management cycle.

Ocean storage capacity is not very large if you put carbonic acid in the ocean, because the ocean pH would change. On the other hand, if you deliver the CO2 as calcium, magnesium or sodium bicarbonate, then the ocean pH would not be affected. You would actually slightly increase and therefore restore the pH. Underground storage is claimed to be very large, but it is not clear whether the public will accept large scale underground storage. Lastly, we are looking at options for forming carbonates on land which can then be stored as solid carbonate for extremely long times. I believe this mineral sequestration route is the safest (but I am biased, because I first developed it) but it is also the most expensive route. However, it certainly has the capacity to tie up all the CO2 you could ever produce.

Question 1: As an average person, is there anything the general public can do to help reduce an individual's carbon footprint and then help remove carbon from the atmosphere?

> You can try to be more efficient and avoid waste, this will gain the world time to clean up. Secondly, you can help as part of the public to convince the world that we actually need to address this problem. There are still plenty of people who think climate change is a hoax, and there are even more people who think the only thing that can be done is to stop using energy. Instead, we need to convince the world that a technological fix to the problem is not all that bad.

Question 2: Could there be a feasible way to have relatively small carbon collectors, in comparison to full size, placed ontop of different buildings on university campuses so that way universities (like ASU) who are conscious of their environmental impact, could then lead the way in gaining public acceptance of removing and collecting the carbon and carbon dioxide from the atmosphere?

> Yes, and it may be even financially attractive once the first units become real. Consider for example ASU's large research effort in algae fuels and algae cultivation, (or maybe the effort in Greenhouses at the University of Arizona). In these systems you need CO2 and right now we spend a lot of money to by this CO2 from a gas company. Would it not be neat to get it directly from the air at the side. We are working toward this goal with Bruce Rittmann's group as we are developing a system to feed CO2 into an algae bio-reactor.

Question 1: Fascinating technology! Would an increased ability to remove carbon from the atmosphere simply encourage people to burn more? Or would that be inhibited by government regulation?

> I would turn the question around. Does it look to you like the world reduced its emissions of CO2 because it so far did not have the ability to remove carbon from the atmosphere. Empirically it pretty much looks like we ignored the problem in the past. Therefore I doubt that we would increase emissions, if air capture technology would be successfully demonstrated. Thirty years ago you could have used CO2 as an excuse for inaction. By now we are already over the top. Since we already overshoot the safe limit of CO2 in the air, you can actually point out that continuned CO2 emissions will cause damage that is completely avoidable. Before you could have argued that things can never stop so you may as well keep going. Yes, you need regulations. In my view the simplest form of regulation would be that for every ton of carbon coming out of the ground another ton will have to be put back. In other words, fuel extractors (and possibly fuel importers) must purchase certificates of sequestration to get rid of the CO2

Question 2: How scalable is this system, as in, have you looked into the diminishing return of cost effectiveness of the given size of a unit?

> The honest answer is "No." We haven't developed the prototype to the degree that we can really analyze its scaling. However, we have some ideas. First, we are passive and rely on the wind. Therefore, we need to have an intake which can see a large volume of air, moving through the device at relatively low speed. So the frontal area is quite large. A ton-a-day device operating at 1m/s and about 33% recovery needs $50m^2$ of frontal area. You could make a device that is 10,000m2, but that is quite large physically, but it is not very large in terms of CO2 collected. So our goal is to scale up in numbers rather than in size. We would like to fit into a standard shipping container, and a one-ton-per-day device can do that. We can put several thousand on a square kilometer, but we scale up by mass production rather than unit scale. Cars have done very well that way. They are far cheaper than they should be when compared to large scale industrial equipment. For example a car engine costs about $10 per kW, whereas a large coal plant costs about $1,500 per kW. So mass production seems to be a good way of scaling up.

Question 1: What other viable options have been proposed other than air capture?

There are several different ways of doing direct air capture. People have suggested to pull CO2 out of the ocean. Since the ocean surface is in close contact with the air, that would serve the same purpose. The argument in favor is that CO2 in the ocean is more concentrated in the sense that there is about 100 times as much per unit volume. But it is also more dilute, because carbon in the ocean is one molecule per 25,000, whereas in the air it is one molecule per 2,500. So it depends: if your method of capture is sensitive to the density the ocean is your place; if your method is sensitive to the dilution, then air your better choice. The next option is to grow biomass, which is another form of carbon removal. People have then suggested to form biochar. A particular variant of this approach is to fertilize ocean water in the hope that increased biomass production will lead to the sequestration of CO2 that has been taken from the air. The problem is that this carbon storage is quite short lived. If on the other hand you successfully sink that carbon than you risk consuming the oxygen that is available at the deeper ocean as bacteria digest all this excess biomass and this could lead to anoxia at intermediate depth in the ocean. All other options I am aware of can stop emissions, by giving up on fossil fuels, but they cannot return back to levels of CO2 that were lower. Of course, if you wait long enough, nature will take care of the problem, but this will take thousands of years.

Question 2: Why is air capture the strongest option other than pricing?

In a way it sets the price. If you demand that CO2 is cleaned up, if all else fails you can get it back via air capture. Furthermore, it is clear that for some CO2 this is the only option. Therefore, this is the marginal cost of balancing the CO2 budget. If you have an alternative that costs more, than you would not use it. If you have an option that works in some places that is cheaper than of course you will use it. But if you need to capture one more ton of CO2 that is what you will have to pay for it. Assume for a moment that air capture does not exist, then this CO2 will end up in the air, unless the cost of CO2 is even higher than that. So air capture is more powerful than just pricing CO2. If there is no way of getting rid of CO2 then pricing CO2 will just reduce but not eliminate emissions. Air capture combined with sequestration will remove the CO2 and thus balance the carbon budget. The cost of emitting is then equal to the cost of capture + sequestration. This cost may motivate you to consider alternatives that are cheaper. For example improved efficiency, or a transition to non-fossil energy sources, but whenever this turns out to cost more than capture and storage it will be available.

Question 1: If the carbon dioxide were able to be stored without being destroyed, would the earth start to create more on its own, and how?

> I am not sure I understand the question. It is not entirely clear to me what sets the CO2 level in the atmosphere. There clearly is an interplay between CO2 release by geological processes and CO2 uptake by weathering. On top of it there is a feedback cycle going through biomass. What actually sets the level is complicated. For example, the ice age had a lower CO2 concentration. Is that because the ocean is colder and holds more CO2 or is it another part of the control cycle? I don't really know.

Question 2: If we could despose of it, would sending it to space somehow be a viable option, and would getting rid of it be worth the amount of money it would take to send it off?

> Sending CO2 to space would be counterproductive. The speed of something in low Earth orbit is about 6km/s, therefore the kinetic energy is 18 MJ/kg. You added another MJ/kg in potential energy. If you go higher above the Earth the total energy input into the CO2 would be even higher. The heat of combustion that made the CO2 is a little less than that. So you would not have the energy to send it out, even if the system were perfectly efficient. On the other hand rockets are very inefficient. Your energy input is nearly 100 times larger than the energy you imparted on the payload. So sending CO2 into space would require far more energy than you got from it. So what energy did you use the ship it out? And why did you not use all that energy to satisfy your energy demand?

Question 1: What can the information you have collected on the CO2 cycle tell us about the CO2 cycle on other terestrial planets? Is it fundamentally the same?

> The carbon cycle on Earth is very much shaped by life. So it is likely very different from carbon cycles on other planets, at least those we know.

Question 2: What is the most exciting technology or public policy right around the corner that excites you the most?

> I believe that automation, robotics, computer control and artificial intelligence will completely change how we construct infrastructures. Combine this observation with a need of rebuilding the energy system, and you have very powerful forces at work that will revolutionize how we live.

Question 1: If you could set a national policy regarding carbon capture, would you prefer an industrial scale design, or a micro scale design, and why?

I think it is better if policy makers do not try to micromanage technical development. My bet is that small (but not micro) mass produced systems are likely to carry the day, but I believe you can leave this to the markets to figure out. A good policy would require that the carbon budget is balanced. In other words, I would advocate for certificates of sequestration that need to be purchased before you can bring more carbon into the environment. I would not specify how this should be done.

Question 2: You mentioned a possible 10 million unit per year production of the direct-air-capture devices. At this scale, what would be the approximate per-unit cost?

It is a still a little early to estimate that. However, let's give it a try. The rough rule of thumb is that the cost of a 2Nth unit is 80% to 85% of that of the Nth unit. So let's say when we quote an initial price, we mean the price after 10 units have been built. That means that in order to reach the first ten million units, you went through 20 doublings. So the price of the last unit would be between 1% and 4% of the original price. After that you might be close to building 10 million units per year, but that may require a few more doublings. So if we started at $200K for the first unit (a little on the high side), we would come down if we follow the learning curve to between $2000 and $8000 for a unit. However, you might assume that there is a bottom to that cost curve and if I had to pick it, it is between $5,000 and $10,000. However, that is pretty much speculation on what the raw materials in the unit cost. So ten million units might cost you $100 billion per year. The world spend about three trillion dollar on oil per year when oil prices hovered around $100 per barrel. It dropped to less than a third of that in the last few years.

Question 1: Logistically, how would we be able to gravitate towards alternative fuels? For example, if I want to keep my collector's car, will there only be biodiesels or other types of fuel at the pump, or will stations need to be retrofitted to change with the culture?

If you rely on air capture to balance the carbon budget, you do not need to change the fuels you sell at the pump. Of course, things can still change over time. You will be hard pressed to get the 100 octane fuel, which was pretty common when your high performance collector's car was built.

Question 2: Do you feel that there would be more resistance to the negative emissions standard from big corporations, or the general public, and what sort of incentives would you recommend for a majority of the population to accept these changes?

Hard to tell. I don't think, things are all that uniform. Different companies will have different motivations to support or resist this change. The same can probably be said about people. You will have to convince all parties that the change is necessary.

Question 1: What if the emissions became more than 450 ppm, what would happen to Earth?

I don't think 450 ppm is a magic boundary. It represents a gradual change. Take for example the speed limit. In most cities it is around 30 miles per hour. Nothing horrible happens at 35 miles per hour, but the risk of an accident and the potential harm of an accident increase as your speed goes up. You may start to destroy coral reefs in the ocean. You will see an accelaration of glacier melting, which in turn results in ocean rise, which will cause flooding. Hydrological cycles tend to intensify. And regions that are used to grow crops will lose productivity because average temperatures are too high for productive growth, at a time where the food system will be stressed. What exactly will be the thing that gets people's attention is hard to predict.

Question 2: What is the general chemistry behind air capture? How is it done?

Long question. I suggest you read some of the papers. Briefly, all the approaches use a sorbent that binds CO2 as air flows over it. In our case the sorbent is very moisture sensitive. It binds CO2 very well when it is dry and releases it again when it is wet. What happens is that the hydration clouds around the ions shrink when water is removed and this changes the relative energy of the various anions, specifically, carbonate, bicarbonate and hydroxide. At some point it pays to break up one of the residual waters and form an hydroxide ion and bind the proton to the carbonate forming a bicarbonate. If there is plenty of water, the reverse reaction dominates. Our molecular dynamics calculations back this up.

Question 1: With the issue of removing carbon from the ground, how do you replace it in order to rebalance the system?

You put the CO2 back into the ground, you dilute it into the ocean, ideally as a bicarbonate salt, or you form carbonates. See the answer higher up, where I answered a similar question.

Question 2: Once we reach 450 ppm, what changes will we see in the enviornment if we do not begin assessing the issue?

See above.

Question 1: How can we effectively reuse all that collected CO_2?

If you want to reuse all the collected CO_2, you effectively have to stop digging up CO_2. There only very few ways to consume a lot of carbon. The first is to make fuels from CO_2. This implies you are using renewable energy and some fraction of that energy is used to convert CO_2 and H_2O into fuel. The fuel is useful to store energy for times there is not enough renewable energy and to deliver fuel to the transportation sector. Liquid fuels have the advantage that they can be readily stored and shipped. Another way of storing a lot of carbon is to tie it up in the world's infrastructure. Right now about 10% (I believe) of the oil in a barrel will be used for making asphalt. What if you made this from CO_2. (It would be very expensive).

Question 2: Does the shape of the collector affect its effectiveness?

Yes it does. You want a careful balance between contact time and optimal flow. You want to make sure that the wind can push air through, but not blow the system over. So optimal aerodynamic designs are important, but we haven't done much more than the basics.

Question 1: Where do you see this type of science 10 years from now if we do not change the way we do things with carbon?

I suspect sometime in the next ten years the climate change issues will start hurting. For example, droughts like the one in California could become very normal. As the cost of adaptation starts to rise, the interest in solution will go up.

Question 2: Can these Captures detect other types of elements? if not, why spend all this money and make a big product if they can only do one thing when we might be able to expand their uses?

I believe that this one problem is big enough to deserve its own solution. For example would you suggest we should not vaccinate against small pox, because the vaccine does not help with the common cold? Whether or not there are other applications I don't know, yet. However, the technology is still very new, so give it some time to find other applications. We can capture other chemicals, but we haven't found another example that would be really interesting.

Question 1: How do you plan to solve the issues of the machines being damaged from high wind days?

Our apparatus is designed to go through two stages in the cycle. In the first the material is exposed to the wind where it dries out and absorbs CO2. In the second stage it is collapsed into a closed box, where it is exposed to water and regeneration is initiated. If the wind speeds are so excessive that it is not safe to expose the material to the wind, then it has to stay in the regeneration chamber. This is similar to a windmill that turns itself out of the wind, when the wind speeds are too high.

Question 2: What would a time frame be until we the public could see one of these in use?

We had a small unit operating on the unit, but it was not shown to the public in use. We aim to make this possible for the next version, which we are currently working on. So it should happen later this year.

Question 1: In your experience, do skeptics of climate change have less of an outrageous reaction to the proposal negative carbon emissions research as opposed to something like alternative fuels when it comes to addressing the issue of climate change?

I think it is harder to convince a climate skeptic on negative emissions. And that also makes sense. I can make good arguments for solar energy that have nothing to do with climate change. For example, I can argue that it reduces our dependence on foreign oil. Negative emissions only make sense if climate change is really a problem.

Question 2: If carbon dioxide was removed through negative carbon emissions and stored in the Earth's subsurface or altered into carbonate salts, is there anything that could release it back into the atmosphere, like a large earthquake? Or would it take a force greater than what the Earth could produce on its own and therefore isn't a concern?

Are you worried about the oil and gas in the ground? Probably not. However, things can come back out; think of a volcano. It would be a rare occasion, even for gas stored underground. But accidents have happened in the past. Like in anything else you need to manage your risks. There is a demonstrable risk of keeping CO2 in the atmosphere.

Question 1: Does temperature affect the concentration of CO_2, and if so, how?

On a short time scale the answer is no. Warmer air does not produce CO_2. On the other hand, warmer oceans release CO_2. And if you wait long enough, this will affect the CO_2 in the air. During the ice age the CO_2 in the air was lower. But the details of these feedbacks are not entirely clear to me.

Question 2: How much CO_2 do forests/jungles remove from the atmosphere? Would it make a dent in the CO_2 PPM if everyone in the world planted at least one tree?

A typical tree over its life time might collect a few tens of tons of CO_2. The average person consumes ten to twenty tons of CO_2 per year. So yes, it would make a small dent. But also keep in mind that eventually the tree dies and rots and then the CO_2 is back in the air. Put another way. Most of our CO_2 problem comes from the use of fossil fuels, a smaller part comes from deforrestation. Restoration of the trees, can fix the smaller part, but since it did not really cause the problem, it cannot really fix it. Furthermore, the entire biomass on the planet is about 600 Gt of carbon; most of it in trees. Annual fossil fuel consumption is nearly 10 Gt of carbon. So in 60 years you would have to double the world's forests, which causes its own environmental issues.

Question 1: Once we go forward with implementing the air catch stations, what kind of uptake is needed to sustain the stations, will they need to be replaced going into the future?

In the talk I suggested the last 10 years. Maybe you can make them last 30 years, but like any other equipment occasionally they will need to be replaced.

Question 2: Whats your team's estimate of when you can start manufacturing the stations, considering the political climate and future ccmpaigns?

It is too difficult to predict. It depends on how politics plays out, and how the climate impacts are being perceived. The new thing after Paris is that many people have begun to realize that any solution needs negative emissions. But then there are plenty of people, who still think there is no climate change.

Question 1: Are the CO_2 capture stations autonomous?

If they stay at the scale of 1 ton per day, they must be nearly autonomous. You simply cannot afford to pay a person to keep watching a station. So you need to reach a high level of automation.

Question 2: Is solar technology advanced enough to power the processes required for your proposed CO_2 capture method?

Yes it is, but it would help if it gets cheaper. Energy is a big cost item. But using carbon free energy is helpful, because otherwise we not only capture but also emit, and those two things cancel each other out.

Question 1: Carbon capture and storage sounds like a good plane to get rid of the CO_2 in the atmosphere, but does this plan incorporate a method by which we can rid ourselves of the particulate matter, NOx and SOx pollution?

> No, for that you have to clean up at the source. On the other hand with the exception of N_2O, all the other pollutants are short lived, once you clean up they go away in a short time. CO_2 on the other hand lingers for centuries.

Question 2: Would it be possible to use one of your capture devices underwater as well as on land so that we wouldn't have to wait for the excess carbon to become airborne before we take it out of the system?

> As I noted above, other people are trying to pull CO_2 out of seawater. Our device would not work under water, it needs to be dry. Other machines might. However, we put the CO_2 we emit mostly into the atmosphere. Therefore this is the first place to catch it.

Question 1: While carbon dioxide emissions are important to look at, methane is a much more potent green house gas. Is there any cooperation at an international level to decrease methane emissions?

> Yes there is. It is part of the overall greenhouse gas negotiations. However, it is different from CO_2 in that you need to stop emitting. Once you stopped. It takes a decade for most of the methane to decay and produce CO_2.

Question 2: According to the UK's Department for Environment, Food and Rural Affairs, raising 1 kilogram of beef produces 34.6 kg of CO_2. Taking this into consideration with a global bovine population of 1.5 billion, does this source of green house gas emission need to take somewhat of a priority?

> This depends on your priority. Your car puts out a pound per mile. You will have to balance out all greenhouse gas emissions. From beef production and from driving around in a car. If it costs you $50 to deal with a ton of CO_2 you would add about $1.75 to the price of a kilogram of beef. You think that is affordable? It might even become less, if there were a price on it. Your gallon of gas would cost about 45 cents more and that might make your car a little more efficient.

Question 1: What is the first country you see putting your instruments in place?

> Hard to predict. Sometimes I think it will be China.

Question 2: Are there similar technologies for private use and consumption?

> Not sure what you mean. You could operate such a device at home, but what would you do with the CO_2 you collected. Maybe you could make selters water, or you could feed your own greenhouse in the backyard.

Question 1: What are your favorite ideas of using technologies to reduce the carbon dioxide in the atmosphere?

I give you three guesses.

Question 2: What do you think of the idea of putting massive turbines around the world that literally remove carbon dioxide from the atmosphere?

Why turbines?

Question 1: Do you think it is possible to completely eliminate carbon emissions and still live the same life-style and not sacrafice the convience of current technology. Or do we need to completely change in order to eliminate carbon emissions?

Air capture can completely eliminate carbon emissions. Those emissions that escaped are mopped up again. It can even create negative emissions. The cost is not zero, but it is not very large either. So for an affordable price one can stabilize climate, without sacrifycing the conveniency of modern technology.

Question 2: If the release of carbon dioxide to the atmosphere was outlawed, do you think that the enviroment would revert back to the time before global warming (temperature and weather) or do you think that the enviroment would stay the same and not get any worse?

On a human time scale the effect is nearly permanent. The climate would not revert fast. The warming impact would persist for about a 1000 years before it gradually starts to drop down. If you completely stopped emitting, the CO2 in the atmosphere would gradually drop down, but since the system has not yet equilibrated with the larger greenhouse effect, the warming would still increase for a long time, and it looks like these two effects roughly cancel, keeping the warming impact of a ton of CO2 constant for about a millennium. After that over several millennia the warming would revert and eventually after tens of thousands of years the system reverts to its original state.

Question 1: Understanding that your carbon capture systems work best in dry climates, have you factored in the cost getting the water used to wash the carbon off the substrate into you economics?

> Yes, we have. In the worst case analysis we would desalinate about water. In that case we would have to pay about $5 to $10 per ton of CO2 for water. We are working on using seawater or brackish water directly.

Question 2: Also, it would seem placing these in dry areas makes sense. But once again, I have a water questions. What are the costs associated with separating the bicarbonate from the water used to wash the system? Is that straightforward and can the water easily be 'reused' with a lot of processing to extract the carbon.

> The water cannot hold on to the CO2, so the CO2 actually comes out as a gas. This does not cost us all that much. The water we still have can be reused, but some of the water evaporates and that is the water we have to make up in every cycle. We use a lot of water, but far less than agricultural crops do. So compared to biomass processes, we do a lot better.

Question 1: Are deserts the ideal places where you'll want to place the carbon intake filters?

> For now yes. At least for our approach. There are other technologies which would work better in moist climes then in dry regions. It is a little like wind energy and solar energy, or hydro-energy. Different horses for different courses.

Question 2: Will these carbon filters (the large ones that your talk was mostly on) always be large products or will there ever be a way that we could use them on vehicles/airplanes/etc to filter air and carbon instead? Like a water filter?

> You could make them a lot smaller, but then you need to have a local use for the CO2.

Question 1: Have the somewhat recent "green energy" movements had any significant impact on the carbon readings we get today?

> Difficult to say. The trajectory we are on has been very much near the top of the IPCC predictions. This suggests that the green energy did not help very much. This also goes with the observation that the total amount is not all that large compared to the big players of fossil fuels. On the other hand, I don't know where we would be, if we had not worried about the climate. Lastly, it is worth pointing out that fossil carbon consumption in the last two years did not increase. However, this is mainly driven by the shale gas boom in the US, and changes in China, where coal consumption seems to have stalled. Emissions in Germany went up, because nuclear power is being phased out.

Question 2: Do your models account for possible industrial revolutions in other parts of the world, which would likely increase carbon emissions, or would those ideally happen using some of these newer technologies?

> I am not a modeler, but I do agree with you that industrial revolutions will put a lot of pressure on future emissions. You see this in India and in Africa. I don't think you can make poor people wait and stay hungry until we figured things out. Another good reason to develop options that are affordable.

Question 1: As far as capturing carbon emissions from the air is concerned (in relation to simply cleaning the atmosphere rather than just balancing the cycle) do you see this proposed process as sustainable long enough to allow our technology to out grow CO2 and other harmful emissions? I believe that cleaning the air is top priority (and developing a sustainable market is what I think is the only way to get the world to do so), so my concerns merely rely on the ability to do so efficiently.

> I think air capture can be sustained for a very long time at a very large scale, once it has been demonstrated and implemented. The more difficult question is whether you have enough storage space to hide all the CO2. I expect we do, but if things get in trouble it is there. I believe storage of carbon is the really hard part of the problem.

Question 2: It is possible someone already asked this question and I missed them. For the proposed passive collectors and sorbent materials you mentioned, is the process of fabricating them relatively free of poisons and harmful emissions (similar to those found in the fabrication of solar panels)? If so, then what can the industry do to better encourage its scientists and engineers to develop such technologies without these harmful materials/methods?

> The material we use right now looks quite safe. I don't think it uses very toxic materials, and the resulting products are used in food processing. So they seem to be quite safe. On the other hand, we may rely on different materials in the future. So you have to make safety one of the important considerations when you develop the materials. It does not help to solve the CO2 problem in a way that create even larger problems.

Question 1: How is Co2 stored geologically, and is there anyway of compacting it so that less space is needed to store it?

CO2 stored underground is at a high pressure it has a density which is between 0.5 and 0.8 g/cc, so it is close to the density of water. If you make carbonates, you have similar effective densities. The problem is you make 35 Gtons per year. For water this would be 35 cubic kilometers.

Question 2: What do you see as your biggest obsticale in educating people/govements on why capturing CO2 in the air is the best solution we have available to reduce CO2 emissions.

Convincing them of the need for treating CO2 as a waste product.

Question 1: Will the units be able to turn out revenue (as to be more desirable to a capitalistic nation) or will we have to depend on the government recognizing the urgency of global warming?

The units will only create revenue if governments regulate CO2 emissions, but regulations can be designed to allow for revenue streams. For example, I by law cannot dump my garbage on the side of the street, as a result I hire a waste management company that takes care of my garbage and disposes of it in a professional manner. I pay for this service, and therefore the company has a revenue stream. It would not have that revenue, if the government would not have regulated the disposal of waste. Similarly the government could require fossil fuel producers to show certificates of sequestration for an amount of carbon equal to what they are extracting from the ground. This certificate could be generated by a private company that is paid for its service.

Question 2: If we placed the units in ideal locations (where it hardly rains) will the uneven distribution affect their efficiency?

No, CO2 is very evenly distributed. You can put your collector anywhere, and you will everywhere see about 400 ppm. Variations are quite small. The mixing is much faster than the rate of addition. You could collect all the worlds CO2 emissions in Australia. You could even collect them in Arizona, but then there would be a lot of collectors in a small space.

Question 1: For DAC machines, how long will it have to run before it has captured an equivalent amount of emissions to that which it takes to create the DAC machine itself?

As a rough rule of thumb, the CO2 emissions associated with most products is a few times its own weight, let's say five times. This is a rough estimate. A one ton-per-day device may way 10 to 20 tons. It contains about 5 tons of sorbent. So you may need 100 days for collecting your own CO2. The device should last at least 10 years. So it is a small correction. A bigger effect is the CO2 that is lost from its own energy consumption. If we make liquid CO2 we have estimated that to be on the order of 20% of the captured CO2.

Question 2: What kind of considerations have to be made, in regards to environmental impact, when planning where DACs would be placed? This question is a bit funny because the job of the DAC is environmental impact!

It is not a funny question, it actually is an important question. The device must lower the environmental impact of human activities not raise it. Now it consumes energy, it may have some emissions to the atmosphere. However, from what we know so far these emissions are very small. But we are still early in the game, and we won't really know until we have run some large scale demonstrations. So this is something we have to be vigilant on. I can only say that there need not be an impact, but that does not say that there is none.